X-641-64-347

TM X-55111

PHOTOELECTRIC uvby AND Hβ PHOTOMETRY OF MAGNETIC AND OTHER PECULIAR AND METALLIC-LINE A STARS

BY

ROBERT C. CAMERON

NOVEMBER 1964

NASA — GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

To be published in the Proceedings of I. A. U. Symposium No. 24, "Spectral Classification and Multicolour Photometry," Saltsjöbaden, Sweden, August 17-21, 1964.

PHOTOELECTRIC uvby AND Hβ PHOTOMETRY OF MAGNETIC AND OTHER PECULIAR AND METALLIC-LINE A STARS*

ROBERT C. CAMERON**

Goddard Space Flight Center, Greenbelt, Maryland;

Georgetown College Observatory, Washington, D. C.;

Kitt Peak National Observatory, Tucson, Arizona***

The observations discussed in this preliminary report were carried out with the 16-inch reflector of the Kitt Peak National Observatory in 1962-3 on the intermediate-band uvby system of Strömgren and the narrow-band Hβ system of Crawford. The two systems are described by Crawford in this symposium. Either T. Kelsall or B. Faure assisted at the telescope during most of the observations.

Half of the 600 program stars were selected from the four categories of stars examined by H. W. Babcock [1] for the longitudinal Zeeman effect: (1) magnetic stars, (2) suspected magnetic stars, (3) sharp-lined non-magnetic stars, and (4) stars with lines too broad for detection of the Zeeman effect. Most of the Babcock stars are B8-F0 peculiar stars

*Contribution No._____ of the Kitt Peak National Observatory.
**Visiting Astronomer, 1962-3, Kitt Peak National Observatory.
***Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

with abnormally strong lines of Mn, Si, Cr, Eu, or Sr (denoted here as Bp or Ap), or metallic-line (Am) stars, since these types have provided the most fruitful source of magnetic stars. Also a number of such stars, as yet unexamined for the Zeeman effect and selected largely from the catalogues of C. Bertaud [2], were included in the program, along with a selection of normal, variable, and unusual B3-F0 comparison stars. Considerable data for normal comparison stars was kindly provided by Strömgren, Crawford, and Perry in advance of publication. Altogether about 300 peculiar and 100 Am stars were observed.

The basic parameters of the uvby system are (apart from a zero-point constant) the color index, b-y; the Balmer discontinuity index, $c_1 = (u-v) - (v-b)$; and the metal index, $m_1 = (v-b) - (b-y)$, which measures the influence of metal absorption lines in the violet band as compared with the relatively unaffected blue and yellow bands. For late-F and early-G stars, the metal index provides a measure of the Fe/H abundance ratio; in the present context of earlier-type stars, m_1 will be regarded just as a useful parameter (relatively uninfluenced by space reddening) whose overall significance is yet to be determined.

It is convenient to discuss the observations according to whether a star lies on the hot or cool side of Balmer discontinuity maximum. The dividing line is, for main sequence stars, approximately at b-y = + 0.02 and between spectral classes A1 and A2.

1. THE HOT PECULIAR STARS

All of the Bp and A0p stars and a few A2p stars lie on the hot side of c_1 maximum. The stars plotted in Figure 1 are all peculiar and all

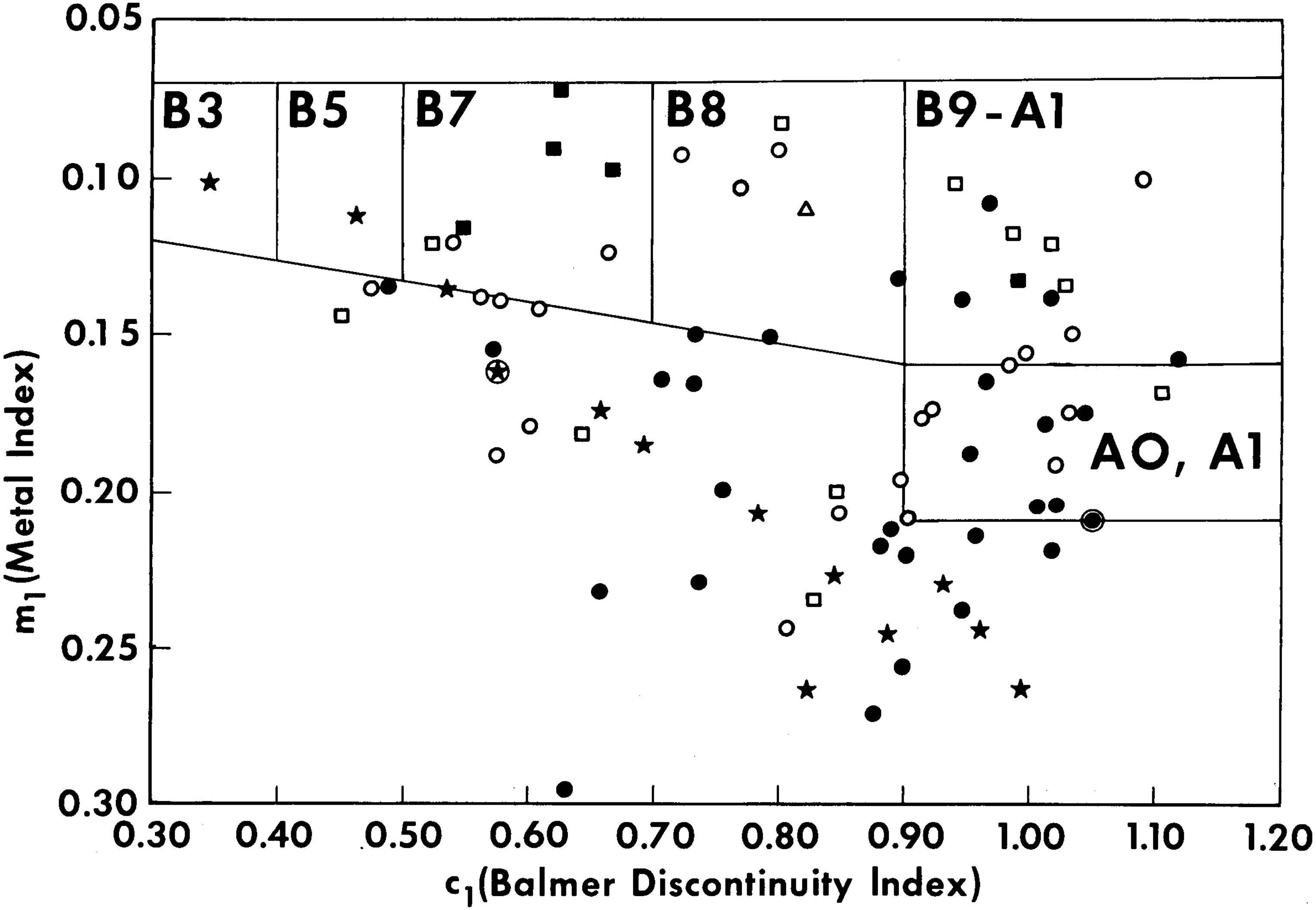

Figure 1. The distribution of the hot peculiar magnetic and broad-lined Babcock stars. Labeled boxes refer to regions occupied by non-peculiar stars of luminosity classes III-V. Legend: ★, strong-field magnetic stars; ●, other magnetic Ap stars; ■, other magnetic Bp stars; ○, broad-lined Ap stars; □, broad-lined Bp stars; △, sharp-lined non-magnetic Ap star.

have been examined by Babcock for the Zeeman effect. The diagram is, for simplicity, a two-dimensional color vs. metal index diagram, with c_1 taken as the color parameter (as it is for normal B stars), since the question of the removal of the effects of reddening from b-y has not yet been examined in detail. Increasing m_1 corresponds to increasing metal absorption. The units are magnitudes.

The suitability of c_1 as a color indicator for the peculiar stars is shown in general, if not in detail, by the following considerations: there is a generally good correlation between c_1 and b-y for unreddened peculiar stars; Searle and Sargent [3] have recently shown that B-V (which is nearly a linear function of b-y) is a very good indicator of ionization temperature in peculiar stars; and peculiar stars exhibiting the high-excitation silicon line, λ 4200, are found generally in the low-c_1 regions. The Searle-Sargent expression,

$$5040/T_{ion} = (B-V) + 0.5,$$

combined with B-V ≈ 1.5 (b-y) and the bluest observed color for an A0p star, b-y = -0.13, shows that ionization temperatures of 16,500 degrees and upwards are appropriate to the hottest of these stars, corresponding to those of B5 and earlier normal stars.

The overall boxed region of Figure 1 is that within which all observed non-peculiar stars of luminosity classes, III, IV, and V were found to lie, with the more luminous stars tending toward the lower m_1-values. The boundaries of the subdivisions, B3, B5, etc., pertaining to non-peculiar stars, are approximate.

The filled symbols stand for magnetic stars; the open symbols stand for broad-lined stars, with the exception of the open triangle, representing 46 Dra, the sole example of a sharp-lined peculiar star with no detectable magnetic field.*

The star-shaped symbols stand for strongly magnetic stars for which an effective magnetic field intensity has been measured at 1500 gauss or greater. Circles refer to Ap stars; squares, to B8p and B9p stars.

In this paper, the magnetic stars will also be considered in their role as sharp-lined stars of presumed low values of the projected equatorial rotational velocity, V sin i, where i is the inclination of the line of sight to the axis of rotation. These stars must be sharp-lined to be detectable as magnetic. Babcock's line-width indices, w**, measured on high-dispersion spectrograms, represent the most extensive data available for the sharpest-lined B and A stars.

The suspected magnetic stars (tabulated later, but not plotted) have line widths that are generally intermediate between those of the magnetic stars ($0.07 \leq w < 0.5$) and the broad-lined stars ($w > 1$).

The photometric discovery criterion implicit in Figure 1 is that any star found to lie below the boxed regions can be identified as a peculiar star without any knowledge of its spectrum. This rather crude criterion

*According to Babcock [private conversation], additional observations of 46 Dra will be necessary before its non-magnetic character can be definitely established. There is the common presumption that all peculiar stars are magnetic and will be detected as such, whenever the spectral lines are sufficiently sharp and the magnetic field is not passing through zero.

**w refers to typical metal line widths near λ4200, measured in angstroms and corrected for the projected slit width. For pure rotational Doppler broadening, V sin i $\approx$ 36 w km./sec.

is subject to further refinement when the three-dimensional array, including β, is more closely examined; for example, it appears that within the A0-A1 box, normal stars may be distinguishable from the peculiar stars by their higher β-values. It is also possible that the intrinsic color, $(b-y)_o$, will be useful as a discriminant.

It is of some importance that the well-studied uvby system, designed mainly for normal stars, is (unexpectedly) very sensitive to the peculiarities of these hot stars, i.e., that an ad hoc system— less suitable for normal comparison stars—is not required to display the peculiarities. In the UBV system, the peculiar stars appear essentially normal and follow the two-color relations for main-sequence and giant stars (see, e.g., Abt and Golson[4]). It is not yet definitely known whether the extraordinary metal indices for the peculiar stars are primarily to be associated with line absorption or an abnormal continuum.

It is also evident in Figure 1 that there is a preponderance of magnetic stars among those with $m_1 > 0.21$. Within this region there are 20 Babcock stars, of which 17 are magnetic. Here we have a second empirical criterion, namely, that a star with $m_1 > 0.21$ has a probability of 0.85 of being certainly magnetic by observations of the longitudinal Zeeman effect.

Some time ago, Babcock[5] made a plea for the use of a photoelectric method of identifying good magnetic prospects in order to reduce the amount of time spent with the large reflectors in examining unprofitable peculiar stars. He had in mind that some of the best magnetic stars also have detectable light variations. The criterion described here satisfies Babcock's request in principle, if not in detail, and is probably more satisfactory, since an appreciable fraction of variable peculiar stars turn out to be broad-lined; furthermore, here only a single observation is required, rather than a series.

It can be seen in Figure 1 that the Bp stars (square symbols) are not necessarily earlier than the Ap stars, but are to be found at generally lower m_1-values. The very predominantly low m_1-distribution of the Bp stars is confirmed by observations of additional stars not plotted. The Bp stars are nearly always Mn or Si stars and have weak fields at best (with the notable exception of the strong-field B9p silicon star, HD 32633, which lies on the lower boundary of the B7 box). Bp stars sometimes exhibit giant characteristics, and altogether it seems advisable that caution be used in lumping the Bp and Ap stars together, as is frequently done.

In spite of certain apparent irregularities in the distribution, it seems that there is no discontinuity between the domains of the peculiar and the non-peculiar stars, generally speaking.

Next we consider briefly the stars on the cool side of Balmer discontinuity maximum, where the magnetic fields are all of moderate to low intensity, with the outstanding exception of that of 53 Cam (5 kilogauss).

2. THE METALLIC-LINE AND COOL PECULIAR A STARS

A substantial number of Am and a smaller number of cool Ap stars were included in the Strömgren-Perry catalogue[6] of 1217 bright A2-G0 stars. Strömgren[7] found that, while the Am and Ap stars may have metal indices that are normal for their b-y color, they frequently exceed those of normal main-sequence Hyades stars.*

The present results confirm those of Strömgren and extend considerably the observed upper limit of m_1: the metal index of the exceptional A5p magnetic star, HD 188041 (b-y $= +0.045$, $m_1 = 0.313$), is 0.11 magnitude above the standard value (cf. Figure 2 of Strömgren[7]). That this star is also the spectrum variable of the longest known period (226 days), is of interest in connection with the possible inverse m_1-V correlation, to be discussed in the next section.

The somewhat less effective analogues of the discovery criteria outlined previously for the hot peculiar stars are as follows: (1) if $m_1 > 0.26$, the star is certainly <u>either</u> an Ap or Am star; and (2) if $m_1 > 0.21$, a <u>known peculiar</u> star has a probability of 0.8 of being measurably magnetic as compared with 0.17 for the somewhat weaker-field and non-variable (in light and spectrum) Am stars. In the range where the Am and Ap stars share the same b-y colors (corresponding to those of normal A3-F0 stars), the ranges of their other photometric parameters are also quite similar. While the two types of stars may be distinguishable photometrically, the problem has not yet been examined thoroughly.

*I am indebted to Dr. Strömgren for access to unpublished observations of cool peculiar stars; the idea for the present program arose largely through examination of his results.

3. ROTATIONAL VELOCITIES OF THE PECULIAR B AND A STARS

Table 1 summarizes the numerical distribution for the Babcock stars according to m_1-range and star group. (Stars south of declination -20° and close visual binaries with unfavorable magnitude differences have been omitted.) The triads tabulated refer to numbers of stars in the following categories: (1) magnetic, (2) suspected magnetic, and (3) broad-lined. The number of sharp-lined non-magnetic stars is given in parentheses.

Table 1. Numbers of Magnetic, Suspected Magnetic, and Broad-lined Babcock Stars.*

Star Group	$m \leq 0.15$	$0.15 < m_1 \leq 0.21$	$m_1 > 0.21$
B8p, B9p	6-3-7	0-0-3	0-0-1
Hot Ap	8-4-11 (1)	17-6-13	17-1-1
Cool Ap	1-0-0	1-3-3	17-3-1
Am	———	2-4-6	4-8-4 (8)

*Numbers of sharp-lined non-magnetic stars are given in parentheses.

The heavy concentration of sharp-lined stars toward high m_1-values is indicated by the following statistics: of the 41 high-m_1 peculiar stars, 38 are magnetic or suspected magnetic; furthermore, 21 of the 41 (51 percent) are ultra-sharp-lined ($w < 0.25$; $V \sin i < 9$ km./sec.) as compared to 9 of 87 (10 percent) for the peculiar stars with $m_1 \leq 0.21$. Comparable line-width statistics are not available for the Am stars, but the relative absence of broad-lined stars in the high-m_1 group suggests that a similar pattern exists.

In an analysis of the photometry of the Am stars, Strömgren[7] takes m_1 as a measure of the "third parameter"—in addition to mass and age, which are given by c_1 and β—which seems to be required for a basic discussion of the spectral properties of the A stars. Candidates for the third parameter in the color range relevant to the Am stars include rotational velocity and magnetic properties, but it cannot here be identified with any quantity characterizing the initial composition. Strömgren then considers the simple hypothesis that m_1 is strongly correlated inversely with the rotational velocity V itself. The circumstance that the highest-m_1 stars (largely Am) all have low V sin i, and that the stars of highest V sin i occur only at relatively low m_1, is <u>compatible</u> with the hypothesis. The amount of data is admittedly small, but one tentative conclusion drawn is that, as a group, the generally high-m_1 and sharp-lined Am stars are really slow rotators and not fast rotators seen pole-on.

An <u>equally good</u> case can be made for the peculiar stars, from the line-width data at high-m_1 previously discussed and the predominantly low m_1-values of Slettebak's[8] stars of high V sin i, with the proviso that the very hottest peculiar stars, with $c_1 < 0.8$ (see Figure 1)—where the highest-m_1 stars are less predominantly sharp-lined—require more detailed study. (All of this data will be discussed fully in the final paper.)

If the inverse m_1-V correlation holds throughout the peculiar star range, the stars along the lower envelope of the c_1-m_1 diagram will be interpreted as just the slowest rotators for their colors (excluding giants), and the circumstance that the strongest-field stars (star-shaped symbols) are to be found preferentially in this region* will suggest that only slow rotators can have strong magnetic fields of the type measurable through observations of the longitudinal Zeeman effect, viz., coherent fields predominantly of one polarity. The broad-lined stars in the lower envelope of the hottest peculiar stars will be explained as slow rotators (as compared with the rapidly rotating normal B stars) but with sin i too high for the appearance of sharp lines. The tentative picture just outlined is consistent with that of the slowly-rotating oblique rotator model of the peculiar stars, introduced by Stibbs[9] and developed by Deutsch[10], wherein the periods of the spectrum variables are just the rotation periods.

An early objection to the oblique rotator—that there exist irregular magnetic variables—has recently lost some force in view of the finding of Steinitz[11] that the magnetic field of the prototype of the β irregular variables, β CrB, is variable with a period of 18.5 days.

The evidence adduced by Abt[12]** that the main-sequence A4-F2 stars include no slow rotators is in accord with the inverse m_1-V correlation.

However, the increasing evidence that the slow rotators among the A and Am stars[12] and B stars[13] are nearly all relatively close spectroscopic binaries is not in accord with the situation for the peculiar

*The appreciably reddened strong-field stars, HD 215441 (34 kilogauss) and HD 215038, are removed by the reddening correction from the B3 and B5 boxes of Figure 1, respectively, to positions below the boxed regions.

**I am indebted to A. J. Deutsch for a discussion of the implications of Abt's recent research and to Abt for permission to refer to it before publication.

stars, which brings us to the following serious objection to the inverse m_1 -V correlation as applied to the peculiar stars.

It was found by the Jaschecks[14] that for the peculiar stars the fraction of spectroscopic binaries among them is deficient by a factor of approximately 3, as compared with normal late-B and A stars. A like deficiency among the peculiar magnetic stars was noted by Babcock[15]. It has been suggested that the deficiency exists because the sharp-lined peculiar stars are just rapidly rotating normal stars seen pole-on, i. e., the sharpness of the lines and the appearance of spectral peculiarities are due to low sin i. In this case, the orbit plane is expected to be nearly perpendicular to the line of sight, making detection of spectroscopic binaries difficult. Other interpretations of the apparent binary shortage are possible, but seem much less plausible.

A definitive investigation of the duplicity of the peculiar stars, comparable to recent studies by Abt for the Am[16] and main-sequence A stars[12], would very probably provide an important step toward the answering of one of the questions central to the understanding of the physics of the peculiar magnetic stars: Are they fast rotators seen pole-on, or slow rotators, or both?

I am indebted to B. Strömgren, D. L. Crawford, H. A. Abt, H. W. Babcock, A. J. Deutsch, G. W. Preston, and R. Steinitz for valuable discussions; to Mrs. J. Burley, for the IBM 7094 reduction program; and to J. C. Golson and C. L. Perry, for obtaining special observations on request.

REFERENCES

[1] H. W. Babcock, Ap. J. Suppl. 3, 141 [No. 30] (1958).

[2] C. Bertaud, Journal des Observateurs, 42, 45 (1959); 43, 129 (1960).

[3] L. Searle and W. L. W. Sargent, Ap. J. 139, 793 (1964).

[4] H. A. Abt and J. C. Golson, Ap. J. 136, 35 (1962).

[5] H. W. Babcock, Publ. Ast. Soc. Pac. 72, 53 (1960).

[6] B. Strömgren and C. L. Perry, in preparation.

[7] B. Strömgren, Quarterly Journal R. A. S. 4, 8 (1963).

[8] A. Slettebak and R. F. Howard, Ap. J. 121, 102 (1955): B2-B5 stars; A. Slettebak, ibid. 119, 146 (1954): B8-A2 stars; ibid. 121, 653 (1955): A3-G0 stars.

[9] D. W. N. Stibbs, M. N. 110, 395 (1950).

[10] A. J. Deutsch, Ann. d'Ap. 18, 1 (1955); Publ. Ast. Soc. Pac. 68, 92 (1956); I. A. U. Symposium No. 6: Electromagnetic Phenomena in Cosmical Physics, edited by B. Lehnert, Cambridge Univ. Press (1958), p. 209.

[11] R. Steinitz, thesis, Univ. Leiden (1964).

[12] H. A. Abt, submitted for publication.

[13] H. A. Abt and J. H. Hunter, Jr., Ap. J. 136, 381 (1962).

[14] M. and C. Jaschek, Zs. f. Ap. 45, 35 (1958).

[15] H. W. Babcock, Ap. J. 128, 228 (1958).

[16] H. A. Abt, Ap. J. Suppl. 6, 37 [No. 52] (1961).